A REAL-TIME STOCHASTIC MTI RADAR SIMULATION FOR DIS APPLICATION

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Abstract

Modeling the stochastic nature of an air-to-ground radar imposes stringent demands on the processor required to implement the simulation. These demands are intensified when the simulation environment must fit the timeline of a real-time radar system. This paper examines a method to model the stochastic nature of the radar system in a Moving Target Indicator (MTI) mode using ground moving DIS targets as input. A prototype of this MTI simulation technique is being developed for incorporation of the Joint STARS radar into a Joint Advanced Distributed Simulation (JADS) environment.

One of the most important performance criteria of an MTI mode is the Probability of Detection (Pd) of ground moving targets in the presence of clutter assuming a constant false alarm rate. Pd is primarily influenced by the target returns signal-to-noise (S/N) ratio. Another important performance feature influenced by target S/N is the location accuracy of the target. This paper develops a method of characterizing target Pd and location accuracy as a function of key radar system variables that can be implemented in the real-time target detection stream of the MTI radar system.

Introduction

New advanced distributed simulation (ADS) systems are being developed with the expectation of revolutionizing the test and evaluation (T&E), and training processes. The ADS concept is to synergistically combine remotely located system and man-in-the-loop simulations so they can be exercised in concert and in real-time. The combined simulation adds affordable realism, as well as, an opportunity to evaluate developmental concepts in a realistic operational environment. The remote simulations are envisioned to be networked through the Distributive Interactive Simulation (DIS) network.

A Joint ADS (JADS) environment was developed to prove the ADS concept through the execution of an end-to-end (ETE) test scenario. The ETE replicates a complete battlefield environment, from target detection to target assignment, target engagement, and battlefield assessment. The Joint Surveillance Target and Attack Radar System (Joint STARS) E8-C platform is a principal component of the ETE test scenario due to its mission to "provide a long range airborne sensor system for standoff wide area surveillance to locate moving and stationary ground targets in support of battle management, and provide target updates for effective and efficient target attacks." The Joint STARS radar will integrate live targets with simulated virtual targets from the DIS in a seamless manner.

Figure 1 shows a typical JADS environment for the ETE test scenario. The E8-C will fly over a test facility where a limited number of controlled targets will be located. A remotely located target / war simulation as JANUS will provide virtual targets onto the DIS through the use of Protocol Data Units (PDU). The Joint STARS radar will enhance the virtual targets for realism by introducing MTI Pd (probability of detection), CEP (circular error probable), false alarm and terrain screening effects. The enhanced target reports are combined with the appropriate live targets for output from the E8-C. This scenario requires the Joint STARS radar system to handle at least 5000 virtual targets in addition to the normally detected live targets under the real-time constraints of the Joint STARS system.

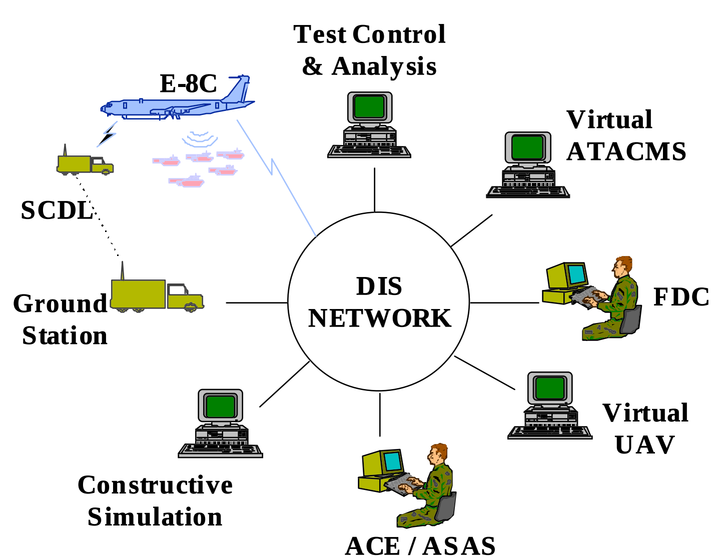

Figure 1. Typical JADS environment

Probability of Detection

This section will define in four parts how target Pd statistics are applied to ground moving DIS targets. The first part of this section develops the relationship of the DIS target to the Joint STARS radar. The second part develops the fundamental relationship of S/N to Pd for the Joint STARS radar. The third part shows how the first two parts may be used to develop a real-time MTI Pd simulation. The last part shows typical results of the real-time MTI Pd simulation.

Geometrical Filtering of DIS targets

Prior to applying Pd statistics to the moving targets, the geometrical relationship of the target to the radar antenna must be determined. The set of ground moving targets received from the DIS network must first be dead reckoned to the current dwell time so that they accurately represent the target's true position. These targets are then filtered to determine which targets reside in the current radar beam footprint. This process can be done by either converting the target from its earth-fixed coordinate system to the radar's polar coordinates or by converting the radar beam information to the target's earth-fixed coordinate system. Since the simulation must handle a very large set of targets and the targets must eventually be reported by the radar in earth-fixed coordinates, the latter approach was chosen in the simulation to save CPU time.

S/N Effects on Target Pd

As previously stated, target Pd can be fundamentally characterized as a function of S/N, and is traditionally developed using the basic radar range equation[1] and subsequently modified to include radar system specifics. For air-to-ground radars, the presence of ground clutter adds a significant complication to the process of detecting a target and must be addressed when developing a design to meet a required Pd. For the Joint STARS system, the probability of detecting a moving target must be considered as a function of target-to-noise (T/N) and target-to-clutter (T/C), where the sum of noise and clutter is considered the interference in the target detection process. Since the detection of moving targets relies upon the Doppler effect, Pd can be developed as a function of T/N and T/C of the Doppler filter in which the target resides.

A set of analytical tools have been developed to measure and predict target Pd for the Joint STARS system under the conditions in which the system is required to operate. One such tool simulates the transmission, reception and processing of a number of coherent processing intervals (CPIs) comprising a set of different pulse repetition frequencies (PRFs) of specified integration length and azimuth beam spacing used to detect and locate a moving target in a clutter background. The target is placed in the desired range and angle location and evaluated over a range of radial velocities. For each CPI, the T/N and T/C ratios are determined for each Doppler filter by convolving the Doppler filter spectrum against the combined clutter, noise and target spectra. From the combined clutter and noise environment, a detection threshold is determined that will allow the system probability of false alarm (PFA) to be met. A Swerling I[4] target model is used with the detection threshold to determine target Pd for each CPI. Assuming each CPI represents an independent look at the target, a composite target Pd is established over 'N' CPIs using an 'M' out of 'N' detection scheme. These analytical tools are non-real-time in nature and have been used in the development of this real-time simulation of Joint STARS MTI.

Real-Time MTI Pd Simulation

Most of the terms in the radar range equation have a fixed allocation and are used primarily as a reference point for Pd determination. However, there are two important loss factors which must be accounted for due to the physical nature of the system; antenna beam broadening loss[2]; and target range. The antenna beam broadening loss results from electronically steering the antenna beam in azimuth and is shown in figure 2. Target range represents the largest S/N impediment to target detection at long ranges due to the two way nature of radar resulting in a $40\text{Log}(R_t)$ loss term. These two features must be compensated for in real time by

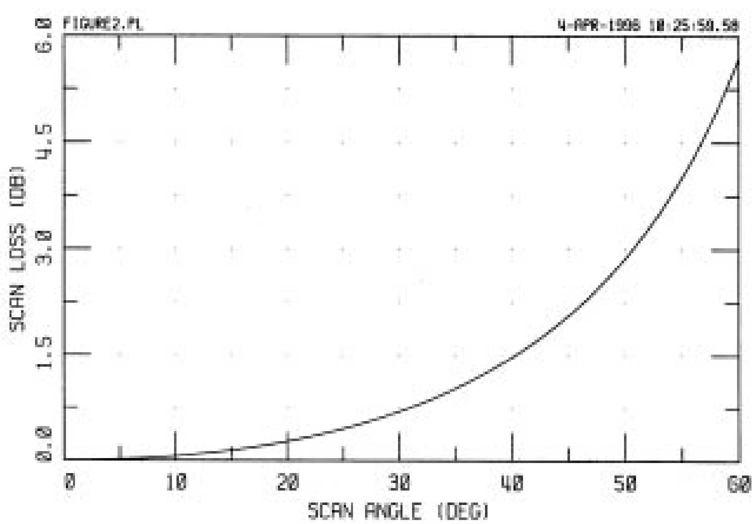

Figure 2. Azimuth Scan Loss

the Joint STARS radar in order to meet the system's specified Pd. This is accomplished by increasing the radar's time on target in both the range and azimuth direction through an optimal combination of beam spacing and integration time. This combination can be

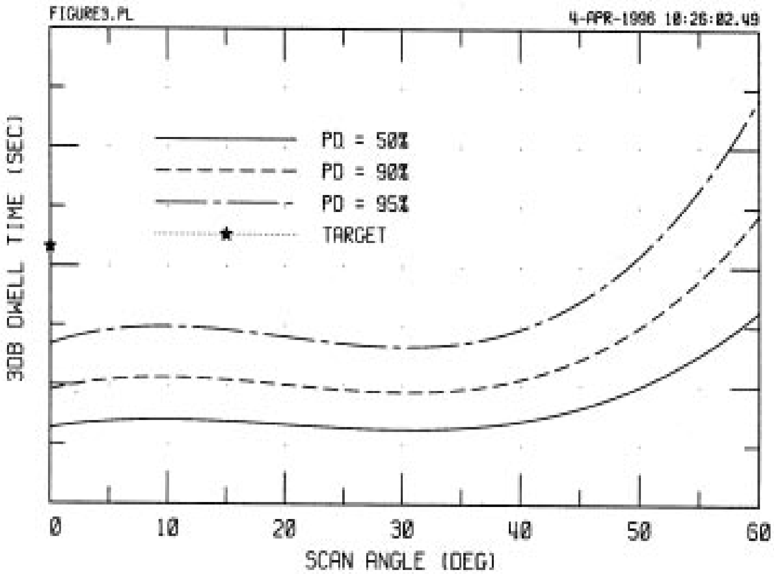

Figure 3. Expand Dwell Time by Azimuth (at system minimun range)

normalized into a single term known as the 3dB dwell time (i.e., the time spent on a target between the half power points of the radar beam).

In order to develop a simulation which inputs ground moving DIS targets into the real-time data stream, the target Pd model must be computationally efficient as well as representative of the conditions from which the scan was initiated. Using the analytical tools described in the previous section, a database of radar operating curves have been developed which define the relationship of average Pd as a function of azimuth, range and dwell time. Since the curves are reasonably well behaved, they have been defined as a Lagrange interpolation series of four points[3]. Figure 3 shows how the 3dB dwell time varies as a function of radar scan angle to meet a specified average Pd, compensating for the azimuth beam broadening loss shown in figure 2. Figure 4 shows how the 3dB dwell time for a given scan angle varies as a function of range to meet a specified Pd, compensating for the two way range loss. The resultant 3dB dwell time may be compared against the radar's actual 3dB dwell time and interpolated between the family of Pd curves to obtain the average Pd of the DIS ground mover given its geometrical relationship (i.e., range and angle) to the radar.

The final part of the MTI Pd simulation is the application of target radial velocity to the Pd process. Low PRF (range unambiguous) MTI radars having ambiguous Doppler measurements, referred to as blind speeds, are caused by the Doppler frequency shift near multiples of the PRF[1]. The blind speeds (V_n) for a PRF are:

$$V_n = \frac{1}{2} \lambda \, n \, PRF \qquad n = 1,2,3...$$

These blind speeds are reduced by employing a multiple PRF design like that used by Joint STARS. A multiple psuedo-low PRF design used by Joint STARS has been selected as a tradeoff between range and Doppler ambiguities, so as to optimize the ability of the radar to detect and disambiguate the velocity ambiguities to resolve the radial velocity of the target.

Figure 5 shows the Pd performance of two different combinations of multiple PRF designs operating at the same range, angle and S / N conditions. Note that the structure of the curves over velocity are completely different, but the mean Pd with respect to velocity is approximately the same. Figure 6 represents the Pd performance of the same combinations of PRFs, but with different S / N ratios. Note that the structure of the Pd curves in figure 6 are identical and that the Pd dips with respect to velocity are exaggerated at lower Pd levels. Since the structure of these curves are difficult to accurately model in real-time, the MTI Pd simulation will store a reference curve for each combination of PRFs used by

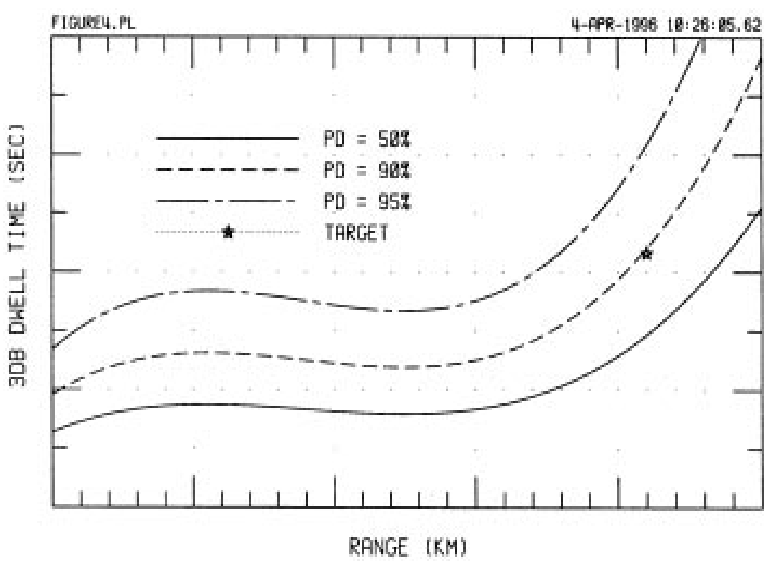

Figure 4. Expand Dwell Time by Range (Scan angle = 0 degrees)

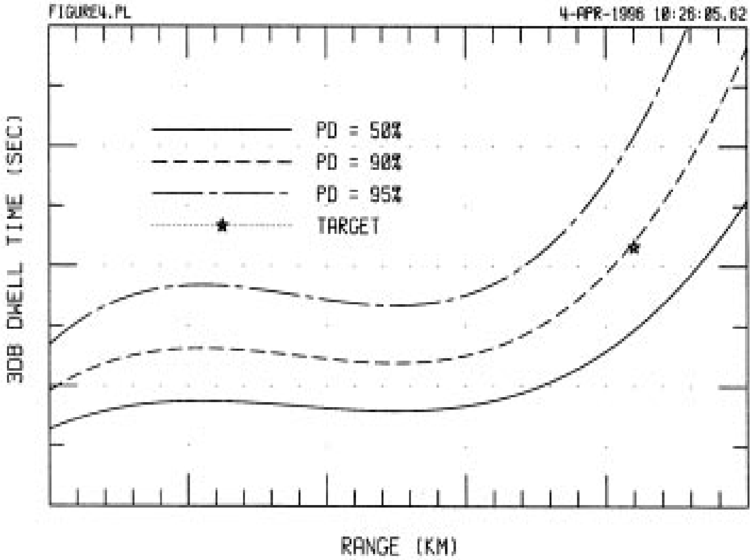

Figure 5. Constant S/N for different PRF Combinations

the Joint STARS radar. Other Pd curves can be derived from the reference Pd curve as follows:

$$Pd_t = \overline{Pd}_t + \dot{R}_f\,(Pd_{rt} - \overline{Pd}_r)$$

where,

Pd_t = Pd of target at velocity V.

$\overline{Pd}_t$ = Pd of target averaged over all V.

$\dot{R}_f$ = Range Rate Factor to enhance Pd dips.

Pd_{rt} = Pd of reference curve at target V.

$\overline{Pd}_r$ = Pd of reference curve averaged over V

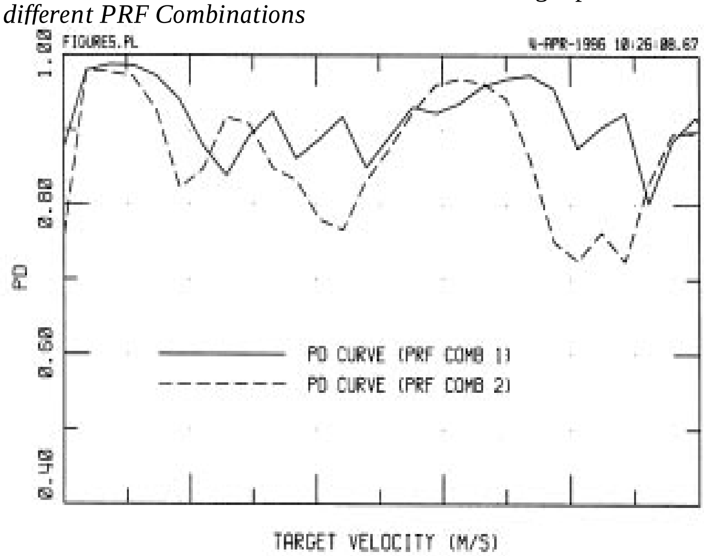

Figure 5. Varied S/N for same PRF Combinations

Real-Time MTI Pd Results

The example given in figures 3, 4, and 7 show a target located broadside (0°) and at a specified range (R_t) and velocity (V_t). Figure 3 states that if the target were at the system's minimum range, the target's expected Pd would easily exceed 95% and in fact approach unity. Note that the expected Pd would be 95% if the target was located at 50° azimuth and 90% at 60°. Figure 4 develops the range versus dwell time curve based on the target's azimuth position of 0°, so that in this example the target's average Pd (wrt velocity) is 90% at range R_t. Figure 7 shows how the target velocity Pd dips are applied from the reference curve to predict the target's actual Pd at the specified velocity. In this example, the target's Pd is predicted by the real-time simulation to be within 2% of the reference simulation for the identical range, angle, velocity and S / N conditions.

In actual practice, the real-time Pd simulation must declare a target detected or not-detected. This is accomplished by comparing the derived target Pd against a uniform random number sequence ranging from 0 to 1. If the random number exceeds the derived Pd, then the target is declared a miss, otherwise it is considered a hit. Figure 8 shows the results of the real-time simulation applied over several hundred scans of a target positioned at various ranges. These results are superimposed onto the reference simulation results to show a high correlation between the real-time simulation and the expected system performance. The results of this method demonstrate

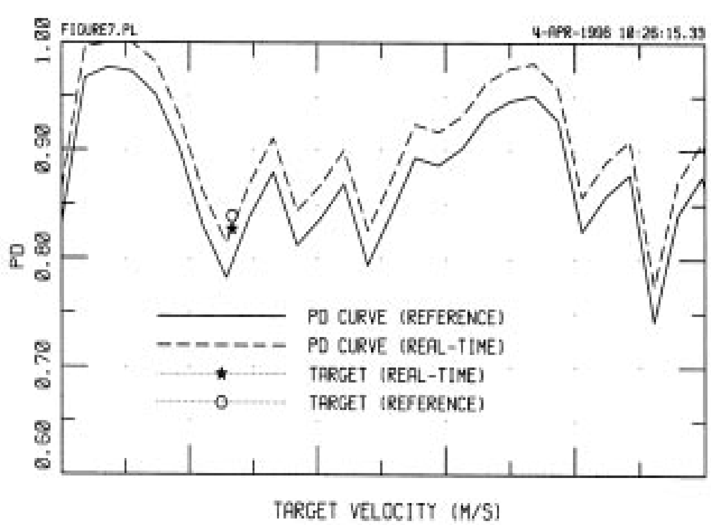

Figure 7. Apply target velocity Pd dips

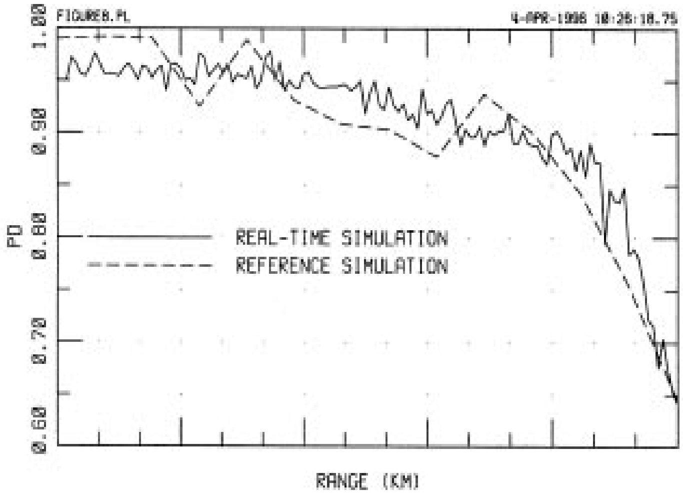

Figure 8. Real-time vs reference simulation

that an accurate simulation of radar MTI performance can be modeled in real-time given the radar dwell time and the target's range, azimuth and velocity.

Location Accuracy

The previous section developed how a DIS target is detected by the Joint STARS radar. This section will define in three parts how the appropriate location accuracy statistics are applied to the detected DIS targets to make them appear to be Joint STARS targets. The first part defines the measurement characteristics of target location using the circular error probable (CEP) method. The second part defines some of the error sources affecting the location of the target based on the target's S / N. The last part shows the typical results of the real-time MTI CEP simulation.

Circular Error Probable (CEP)

The CEP integral has been developed for a variety of systems ranging from assessing when to fire artillery by projecting targets into the shell's "kill-zone", to the evaluation of radar systems and wind sheer[5]. CEP is defined as the radius for which 50% of the targets fall within the radius, and 50% fall outside this radius. In the case of evaluating the location accuracy of a target detected by a radar, the CEP can be derived from the relationship of the 1-sigma down range (S_{dr}), and 1-sigma cross range (S_{cr}) errors as shown in figure 9[6].

S / N Effects on Target Location

There are four classes of error sources which contribute to the location error budget for MTI targets. The first class of errors result from an incorrect range measurement and can be attributed to range resolution, atmospheric refraction and hardware errors. The second class of errors results from incorrect angle measurements due to thermal noise, false patch clutter, hardware and line-of-sight velocity errors. The third class of errors result from vertical separation uncertainties due to platform altitude and ground terrain errors. The last class of errors result from a coordinate system error, resulting from navigation and coordinate conversion errors. These error sources form a linear error model having two outputs (a down range and a cross range error) from which the target's CEP may be estimated[6].

Target S / N has an affect on the angle accuracy of the target. Thermal noise induces an error in the interferometric measurement which is inversely proportional to the square root of the T / N ratio. False patch clutter influences angle accuracy because moving targets compete against clutter from a different azimuth angle than the target. This error is inversely proportional to the square root of the T / C ratio. As with target Pd, curves can be developed which relate angle error as a function of target S / N resulting from a specified dwell time, range and azimuth.

Real-Time MTI CEP Results

The example given in figure 10 shows the expected CEP as a function of range, as derived from the 1-sigma down range and cross range errors. Superimposed on the CEP curve are four targets placed at different ranges such that the actual 1 sigma down range and cross range

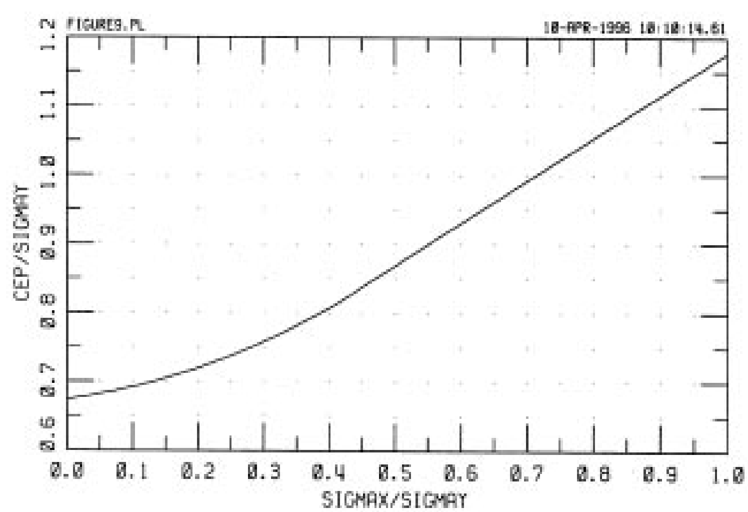

Figure 9. Circular Error Probable (CEP)

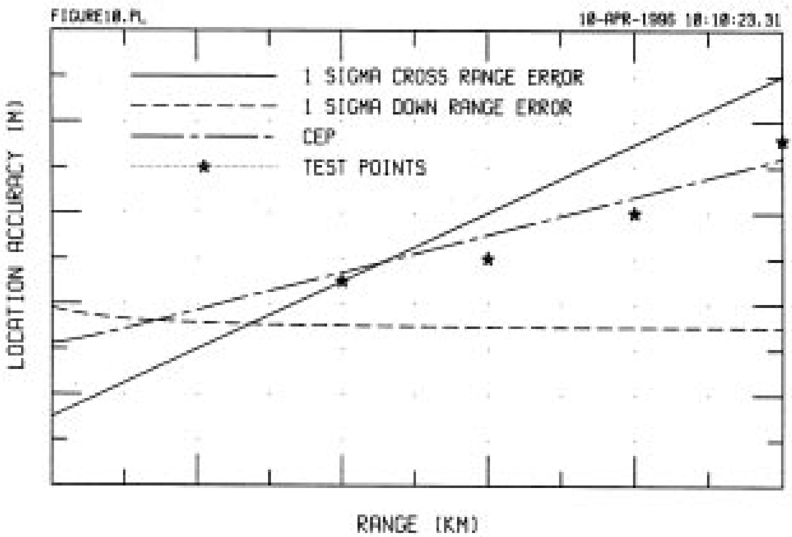

Figure 10. CEP approximation vs range

errors have been randomly selected over several hundred scans of the target. These results indicate a high correlation between the real-time MTI CEP simulation and the derived CEP values. Figure 11 shows the random selection of down range and cross range errors for one of these targets.

One drawback to selecting location errors randomly is that the target appears to have a random fluctuation within a predetermined boundary and can make the target appear too "simulation like". One method used to make the target appear more realistic, is to use a relatively narrow error boundary whose mean is modulated in both amplitude and frequency. This technique has the effect of moving a smaller CEP circle within the larger true CEP circle to achieve the same CEP results with fewer unrealistic random fluctuations.

Conclusion

In this paper, a technique for realistically modeling ground moving DIS targets in a real-time MTI radar system has been presented. Both target Pd and CEP can be accurately modeled in a large scale simulation for a real-time system. Timing studies conducted on radar beam dwells with densely packed targets indicate that the MTI simulation requires only 25% of the dwell time to apply the MTI statistics to the targets, so that the remaining timeline can be used for other simulation effects. The results of this study indicate that large scale ADS systems can be realistically implemented by host systems in a real-time environment.

References

[1] M. I. Skolnick, Introduction To Radar Systems, second edition. New York: McGraw-Hill Book Company, 1980, pp. 23-32, 108, 114-117.

[2] G. W. Stimson, Introduction To Airborne Radar. El Segundo: Hughes Aircraft Company, 1983, pp. 139-141.

[3] I. A. Dodes, Numerical Analysis for Computer Science. New York: Elsevier North-Holland, Inc., 1978, pp. 184-194.

[4] P. Swerling, Probability of Detection for Fluctuating Targets. IRE Trans., vol. IT-6, April 1960, pp. 269-308.

[5] J. T. Gillis, Computation of the Circular Error Probability Integral. IEEE Transactions on Aerospace and Electronic Systems, vol. 27, no. 6, November 1991, pp. 906-910.

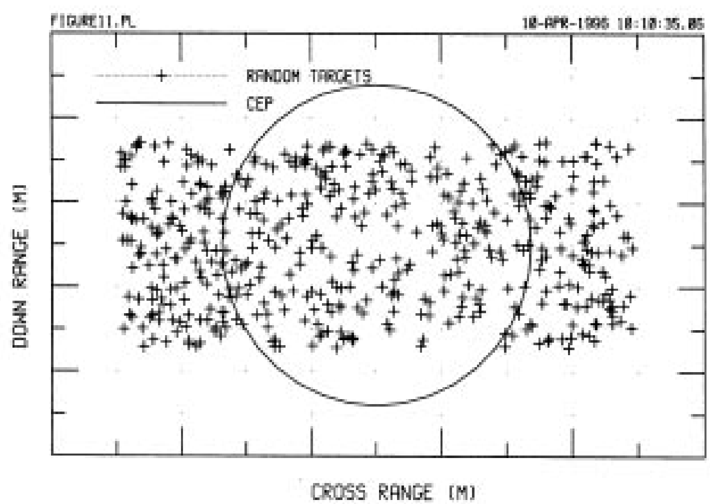

Figure 11. Target 4 CEP

[6] J. S. Przemieniecki, Introduction to Mathematical Methods in Defense Analyses. Washington DC: American Institute of Aeronautics and Astronautics, Inc., 1990, pp. 35-49.